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Inference of fish orientation from broadband acoustic echoes

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ABSTRACT

A new method has been developed for inferring orientation of fish through the use of broadband acoustic signals. The method takes advantage of the small range resolution possessed by these signals, once temporally compressed through a cross-correlation process. The temporal resolution of these compressed signals is inversely proportional to the bandwidth, thus the greater the bandwidth, the finer the resolution. This process has been applied to broadband chirp signals spanning the frequency range 40-95 kHz to obtain a range resolution of approximately 2 cm (compressed down from the original unprocessed resolution of about 50 cm). With such a small resolution, individual scattering features along the fish have been resolved, especially for angles well off normal incidence. The duration of the compressed echo from live individual Alewife, as measured in a laboratory tank, is shown to increase monotonically with orientation angle relative to normal incidence. The increase is due to the increase in range separation between the echoes from the head and tail of the fish. The results of this study show that with *a priori* knowledge of the length of the fish, the orientation could be estimated from the duration of a single compressed broadband echo. This method applies to individual acoustically resolved fish and has advantages over previous approaches as it derives the orientation from a single ping and it does not use a

scattering model. Design parameters for applications in the ocean are given for a range of conditions and fish size.

Keywords: fish, acoustic scattering, broadband acoustics

INTRODUCTION

It is important to know the distribution of orientations of free-swimming fish for two reasons: 1) The orientation distribution of fish correlates with the type of behavior the animal is exhibiting such as feeding or migrating. Knowledge of the orientation distribution of fish under a variety of conditions will therefore contribute to fundamental understanding of animal behavior. 2) Acoustics is commonly used as a means to rapidly and synoptically survey fish. Since acoustic scattering depends strongly upon the orientation of the fish, knowledge of its distribution will help to quantify interpretation of the acoustic survey data.

Measurement of orientation of fish is a challenge. The most direct method involves use of cameras (Huse and Ona, 1996). However, this is logistically difficult, involves a small sampling volume, and can induce avoidance reactions that would contaminate the data. A less invasive approach that would also involve a much larger sampling volume would be the use of acoustical scattering techniques. One acoustical method has involved tracking individual fish over multiple pings, either directly or through echo trace analysis, and equating orientation angle to swim angle (Furusawa and Miyanohana, 1990; Ona, 2001). Another method has involved inferring the orientation, or its distribution, from the scattering data using an assumed scattering model (Foote and Traynor, 1988, Chu et al., 1993; Martin Traykovski et al., 1998).

Clearly, it is most desirable, if possible, to use a synoptic, non-invasive method to measure orientation with the fewest assumptions and least amount of data. Broadband acoustic signals offer advantages for inference of orientation. A genuinely broadband signal, i.e., one with a bandwidth of approximately an octave or greater, is rich with information and is equivalent to simultaneous use of many signals of differing discrete frequencies. Because of this inherent property, there is potential for reducing the number of ambiguities in the interpretation in the data. The challenge is in selection of the optimal approach.

In this paper, we propose a new method that uses broadband acoustic signals to remotely infer orientation of individual fish. We take advantage of a pulse compression technique in which the duration

of the received echo is significantly reduced so that individual features of the fish can be resolved in the time domain (Stanton et al., 1998; Chu and Stanton, 1998). Through simple geometric arguments and *a priori* knowledge of the length of the fish, the orientation of the fish can be determined. No assumptions regarding scattering models are used and the information on the (resolved) fish can be extracted from a single ping. We present broadband (40-95 kHz) acoustic backscattering data collected in the laboratory where the scattering was measured as a function of angle of orientation for a number of individual fish. The duration of the compressed echoes is shown to increase monotonically with angle of orientation over a wide range of angles. Furthermore, the echoes are directly linked to scattering features along the length of the fish. A simple, geometry-based equation is used to describe this relationship and is used to predict performance for a range of system parameters for use in the ocean.

PULSE COMPRESSION PROCESSING OF BROADBAND SIGNALS

Basic properties

The pulse compression processing used herein was applied to fish acoustics by Ehrenberg and Torkelson (1997) and later to zooplankton acoustics in Stanton et al. (1998) and Chu and Stanton (1998). The processing is based on, and is quite similar to, the commonly used matched filter processing. Matched filter processing was developed to optimize detection of a known signal in the presence of random noise (Turin, 1960). It has since been used in a variety of applications, including acoustic propagation and scattering in the ocean (Medwin and Clay, 1998). In the matched filter approach, the noisy signal is cross-correlated with the known or noiseless signal. Given sufficient bandwidth and a long known signal such as a chirp, matched filter processing results in a signal with much higher amplitude and shorter duration than the original signal (Fig. 1). The shape of the processed signal is characterized by a single high amplitude main lobe with smaller sidelobes corresponding to artifacts of the processing. Since this process increases the amplitude of the signal but not the (non-reverberative) noise, the result of applying the matched filter to a noisy signal significantly increases the signal-to-noise ratio (SNR). Also, the width of the main lobe is inversely proportional to the bandwidth of the original signal, greatly increasing the

possible temporal resolution. For example, the width of a processed 0.6-ms-long chirp signal spanning the frequency range 40-95 kHz, is about 0.02 ms. For underwater acoustic signals, this corresponds to an improvement in range resolution to about 2 cm (versus about 50 cm for the original signal).

Application to acoustic scattering by marine life

There are significant advantages associated with processing broadband echoes in a manner similar to that of matched filter processing. As discussed above, the SNR is improved which allows detection of targets at greater ranges. Furthermore, the range resolution is improved which allows targets at greater numerical densities to be resolved. The challenge lies in both implementation of the algorithm and interpretation of the processed signal. Since the target affects the properties of the incident acoustic wave (due to its inherent scattering properties), the ideal noiseless signal with which the received echo should be cross-correlated is not known. This problem has been addressed by simply using the transmission or calibration signal as the so-called "replicate" signal. The resultant "compressed pulse", although different than what a true matched filter would produce, has the same advantages of increased SNR and decreased duration, although to a lesser degree. The increase in SNR, using pulse compression processing has been demonstrated both for fish (Ehrenberg and Torkelson, 1997) and zooplankton (Stanton et al., 1998; Chu and Stanton, 1998).

A very useful consequence of the fact that the cross-correlated scattered signal deviates from a matched filter is the information contained in that deviation. The resultant signal from a matched filter is a single short spike with small sidelobes (Fig. 1, lower right panel). The shape of this signal is what one would expect when the signal had been scattered by a target that is smaller than the compressed range resolution and that possesses a uniform frequency response. However, for an extended target, the cross-correlated scattered signal will, in general, be composed of a series of spikes corresponding to the various scattering features of the scattering object (Stanton et al., 1998; Chu and Stanton, 1998; Barr, 2001). These scattering features are resolved through the inherent increase in resolution of the cross-correlated signal and through an appropriate combination of bandwidth and animal size. Animals such as fish

contain anatomical variations throughout the length of the body. These variations give rise to acoustic scattering, and for long pings, there are generally contributions from structure within the entire body to the total received (unprocessed) echo. Once the echo is compressed, echoes due to the various features will be separated in time, especially for oblique angles (Fig. 2). For angles near normal incidence, the echoes from the various features will tend to arrive at approximately the same time. However, as the angle departs significantly from normal incidence, the time of arrivals will deviate according to the orientation of the fish relative to the direction of the incident wave.

For a sufficiently short compressed pulse, large enough orientation angle, and long enough fish, the arrivals can be resolved. The separation in time, $\Delta\tau$, between the first and last arrival can be related through simple geometry to the length of the fish and orientation angle:

$$\Delta\tau = (2L/c)\left|\cos\theta\right| \tag{1}$$

where c is the speed of sound in water, L is the length of the fish and θ is the angle between the direction of propagation of the incident acoustic signal and the lengthwise axis of the fish (e.g., for tail-on incidence, $\theta = 0$; normal incidence, $\theta = 90°$; head-on incidence, $\theta = 180°$).

The above equation relates orientation of the fish to the extent of the processed acoustic echo. It is very simple and relies only on knowledge of the length of the fish and duration (time between first and last arrival) of the processed echo. This relationship will be explored through analysis of laboratory data in the next section.

EXPERIMENTS

A series of measurements of broadband acoustic backscattering by live individual fish has recently been completed (Reeder et al., submitted). The laboratory measurements were conducted in a 6m X 6m X 6m tank filled with fresh water, using Alewife (*Alosa pseudoharengus*), a swimbladder-bearing fish similar to Atlantic Herring (*Clupea harengus*). The 17 fish, all insonified separately, were all similar in length with an average caudal length of approximately 22 cm. All measurements involved the use of a pair of closely

spaced broadband transducers, one used as a transmitter and the other a receiver. A shaped, linearly swept frequency modulated signal (chirp) spanning the frequency range 40-95 kHz was used. The scattering was measured over all angles of orientation (one-degree increments) in two planes of rotation as the tethered fish were rotated within the acoustic beam. The anatomy and morphology of the fish were characterized through a combination of physical measurement, dissection, traditional x-rays, computerized tomography (CT) scans, and phase contrast x-rays. Details of the experiments and results are presented in Reeder et al. (submitted).

A particularly noteworthy result of the experiment was the ability of the system to resolve individual scattering features along the length of the body of the fish (Figs. 3, 4). As mentioned above, the range resolution of the unprocessed 0.6 ms ping for this laboratory system is approximately 50 cm. After pulse compression, the resolution is about 2 cm. For the 22-cm-long fish with major features such as the skull and swimbladder separated by more than 2 cm, those features were acoustically resolved in the compressed pulse. The general trend of all data was broadly similar in that near normal incidence (dorsal/ventral plane or lateral plane), the compressed pulse signal was a short single spike. Once the orientation was varied well away from normal incidence, the single spike separated into a series of peaks. These observations are consistent with the fact that echoes from scattering features along the body will arrive at approximately the same time at angles near normal incidence. Once the orientation is well away from normal incidence, anatomical features closer to the transducers will produce echoes that arrive sooner than the features at the far end of the body.

All data showed the trend of monotonic increase in separation between the first and last arrival ($\Delta\tau$) relative to orientation angle for angles out to 40-50 degrees from normal incidence (Fig. 4). At angles near end-on (tail-on or head-on), the relationship between orientation angle and peak separation is more complicated and requires an equation such as Eq. 1 to account for the scattering geometry (Fig. 5). Near end-on incidence, even this equation does not adequately describe the separation, because much variability is seen in the data. This deviation between the data and model is due to the fact that at near end-on incidence, the echoes from the scattering features near the far side of the body are shadowed and

therefore possibly not detected. Equation 1 does not account for that phenomenon. However, since there is no shadowing near normal incidence and, given the consistency of the data in that region, there is potential for extracting orientation information from the time signature of the compressed pulse output.

RECOMMENDATIONS FOR FIELD APPLICATIONS

The data show a trend of monotonic increase in the time separation between first and last arrivals of the compressed pulse output and orientation angle near normal incidence (Figs. 5, 6). Given this consistency, there is potential for extracting orientation information from a processed broadband echo. A few questions remain, such as what are the accuracy and precision of the result and how does one design an optimal system to take advantage of such a method? The answers involve the bandwidth of the system, distribution of scattering features with respect to depth within the fish, and artifacts in the echo due to scattering-related interference phenomena.

Although there is a general trend of monotonic increase in the time separation between the first and last echoes with angle of orientation near normal incidence, there is variability about that trend. There are several possible causes of that spread, one being related to the experimental approach. This experiment involved live fish constrained in an acoustically transparent harness. The harness was made tight enough to constrain the fish within the acoustic beam, but loose enough so as not to cause too much stress on the fish during the measurements. Movement of the fish was very apparent in some of the data (not shown). It is reasonable to believe that, although the harness was rotated in one-degree increments, the fish may have moved at least that much in the course of the measurement so as to cause error in the reported value of orientation.

Other sources of variability involve location of the scattering features and interference between them. This is not a laboratory artifact and will occur in the natural ocean environment. Our model assumes that the scattering features in the fish are all located along its length-wise axis. Thus at normal incidence, the associated echoes would all arrive at precisely the same time. However, anatomical features are distributed throughout the depth of the body of the fish and these scattering features vary in

thickness. The composite effect of these two facts results in echoes to arrive at *approximately*, but not exactly the same time when the fish is at normal incidence. The error associated with this is bounded by the thickness of the fish and will certainly be associated with a small fraction of the thickness. Furthermore, due to interference between the arrivals, there will be some variation in the leading or trailing edge of the first and last arrivals of the compressed pulse, respectively, causing further distortion of the results. The error associated with this will be bounded by the temporal resolution of the compressed pulse and will be somewhat smaller than the resolution. Finally, significant scattering may not necessarily arise from parts of the fish near the ends (especially the tail), resulting in an effective acoustic length for use in Eq. 1 that is shorter than the true length. If not taken into account, the error in inferred orientation angle would be approximately 5-10% for the fish and acoustic parameters used in this particular study.

One important limiting factor in this approach involves the bandwidth, which dictates the temporal resolution of the process. As mentioned above, the resolution is inversely proportional to bandwidth of the signal. It is therefore very important to use a system with a very high bandwidth. The 2-cm range resolution of the processed echo in the system described herein resulted in a threshold of about 4 degrees for the 22-cm-long fish (Fig. 6). Increasing the bandwidth of the system would decrease the threshold to the point where other limitations involving the non-colinear nature of scattering features became important.

Choice of bandwidth of the system should therefore be based on the expected size of fish and corresponding deviations of scattering features from a straight line, and desired threshold of detection of orientation angle (Table 1). It is important to stress that the criteria involving bandwidth are independent of the particular frequencies involved (e.g., a 100 kHz bandwidth could be derived from a 50-150kHz system, or a 150-250kHz system). Since it is easier to fabricate efficient high bandwidth systems at higher frequencies because the corresponding *fractional* bandwidth is smaller, then the trade-off between higher frequencies and shorter range of detection must be considered (signals at higher frequencies travel shorter distances).

Finally, for a practical field system, the effects of the beampattern must somehow be accounted for, since beamwidths are a strong function of frequency. This can, in principal, be accomplished by several different methods. One method, using conventional technology, could involve simultaneous use of a narrow beam split-beam echosounder collocated with the broadband single beam system. The split-beam system could be used to locate the position of the fish in the single beam, and the effects of the beampattern of the single beam be removed. More advanced approaches could involve development of a broadband split-beam system or a system with a frequency-independent beamwidth.

SUMMARY AND CONCLUSION

We have conducted laboratory measurements of broadband scattering by swimbladder-bearing fish as a function of angle of orientation. The temporally compressed echoes had a 2-cm range resolution and were able to resolve individual scattering features within the fish. We have observed that the time separation between the first and last returns of the compressed echoes was strongly correlated with angle of orientation for angles near normal incidence. Using that information, we conclude that the orientation of individual (resolved) fish can be inferred from the processed broadband echo from a single ping. Although some of the error in the inference is associated with an artifact of the laboratory measurement (movement of the fish within the harness), there is also error associated with the non-colinear nature of the scattering features along the length of the fish as well as interference between unresolved features. We recommend that the bandwidth be chosen to be as large as possible until the range resolution of the processed signal is comparable to the error associated with the noncolinearity.

In conclusion, broadband acoustic signals are rich with information. As demonstrated in this paper, one important quantity that can be inferred from a single ping is the orientation of resolved fish. Advantages of this approach over others are that only one ping is required and a scattering model is not required. The design criteria of such an acoustic system involve the tradeoff of bandwidth and desired threshold of orientation, as well as accounting for non-colinearity of features along the fish and desired range of detection.

ACKNOWLEDGEMENTS

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Table 1. Bandwidth required for a range of minimum inferred orientation angles and two lengths. Actual minimum angles will be larger due to other effects such as non-colinearity of scattering features.

θ_{min} (deg)	length (cm)	bandwidth (kHz)
3	20 (40)	72 (36)
5	20 (40)	43 (21.5)
10	20 (40)	22 (11)
20	20 (40)	11 (5.5)

Figure Captions

Figure 1. Broadband acoustic signals: (Upper left panel) Shaped time series of the chirp signal as applied to the transmitter transducer. This signal was used both in scattering and calibration measurements. (Upper right panel) Time series of signal at output of receiver transducer in the calibration setup with the transmitting transducer using the same signal as illustrated in upper left panel and aimed at the receiving transducer. (Lower left panel) Frequency spectrum of signal (in dB) at output of the receiver transducer in the calibration setup. (Lower right panel) Envelope of the autocorrelation function, corresponding to matched filter output, of received signal from the upper right panel. The great reduction in pulse duration of the broadband signal relative to the applied signal in the upper left panel is illustrated. The amplitude is normalized to unity.

Figure 2. Schematic illustration of a compressed echo as a function of backscatter direction. The duration of the pulse is short near normal incidence and longer for oblique angles. Three values of θ (0°, 90°, and 180°) are illustrated.

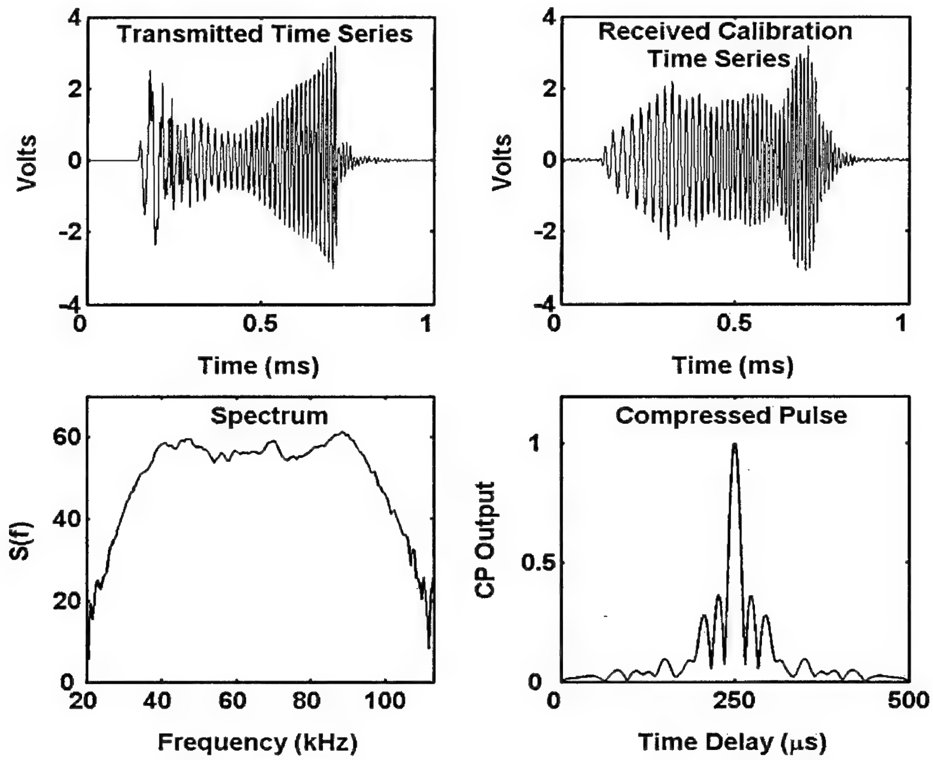
Figure 3. Compressed pulse output from echoes measured from a fish at three orientation angles. At the oblique angle, the echo is composed of two major resolved peaks. "Near normal" and "oblique" incidence correspond to angles that were 5° and 60° off normal incidence, respectively.

Figure 4. Envelopes of compressed pulse echoes for a range of orientation angles (θ) for one fish in one plane of rotation (dorsal/ventral). The straight lines are drawn to illustrate the trend of the locations of the leading and trailing edges of the first and last arrivals, respectively.

Figure 5. Time difference between the beginning of the first arrival of the compressed pulse echo and the end of the last arrival for a superset of orientation angles (θ) shown in Fig. 4. The fish was rotated through 720 degrees. Detection criteria for these outer tails of the time series involved starting or

stopping the count when the time series reached 40% of the maximum level for a given orientation angle. This detection threshold is above the processing sidelobes of the autocorrelation function of the calibration signal as shown in Fig. 1. Equation 1 is superimposed for comparison (with offsets), using an effective acoustic length of 90% of the measured caudal length.

Figure 6. Expanded plot of one angular section of Fig. 5. The minimum angle of inference (vertical dashed line) corresponds to the inverse bandwidth of the signal (horizontal dashed line). The effective acoustic length used in Eq. 1 is 95% of the measured caudal length.



Transmitted Time Series
Volts
Time (ms)
Received Calibration
Time Series
Volts
Time (ms)
Spectrum
S(f)
Frequency (kHz)
Compressed Pulse
CP Output
Time Delay (μs)

Figure 1

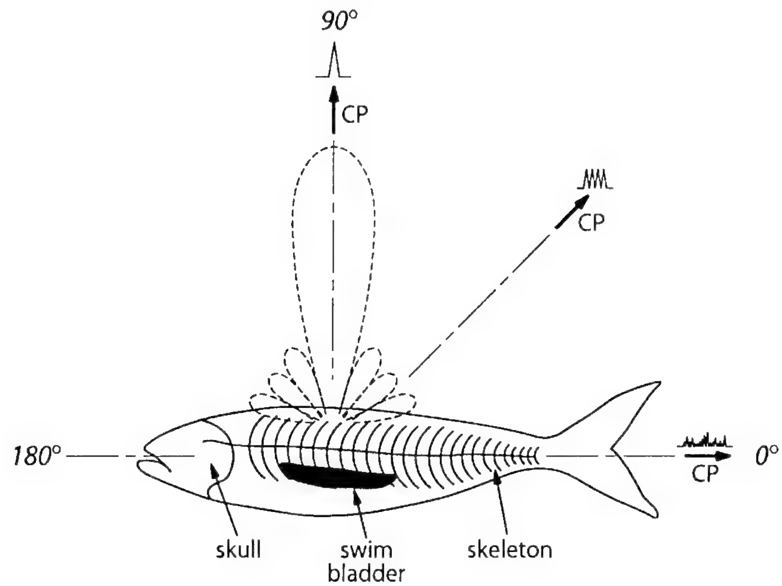


Figure 2

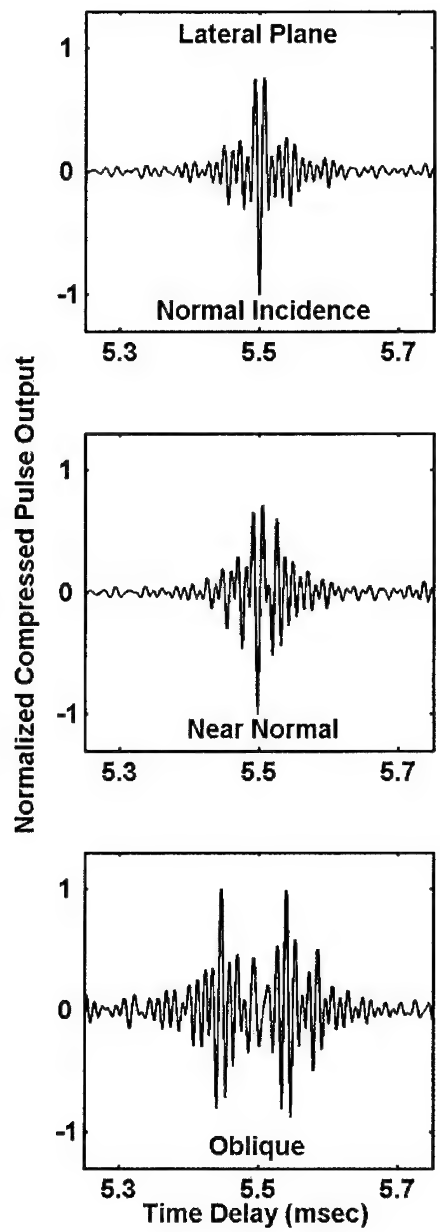
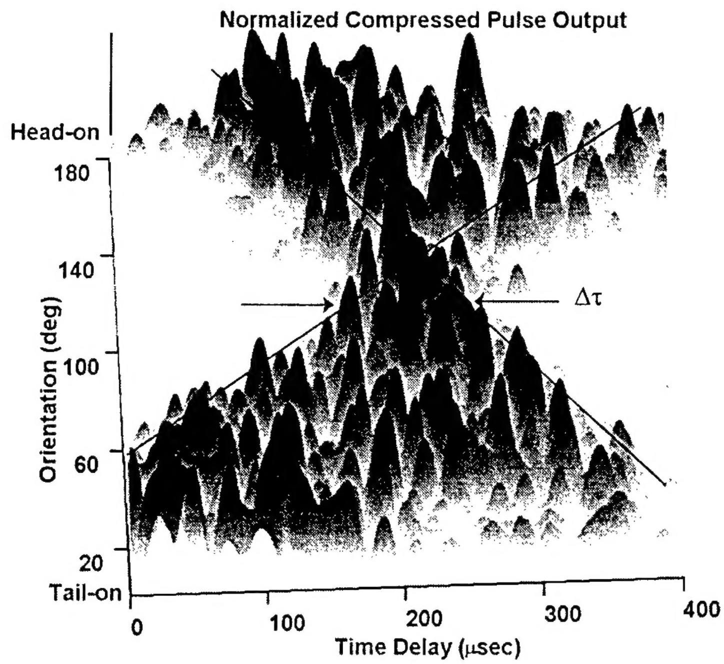
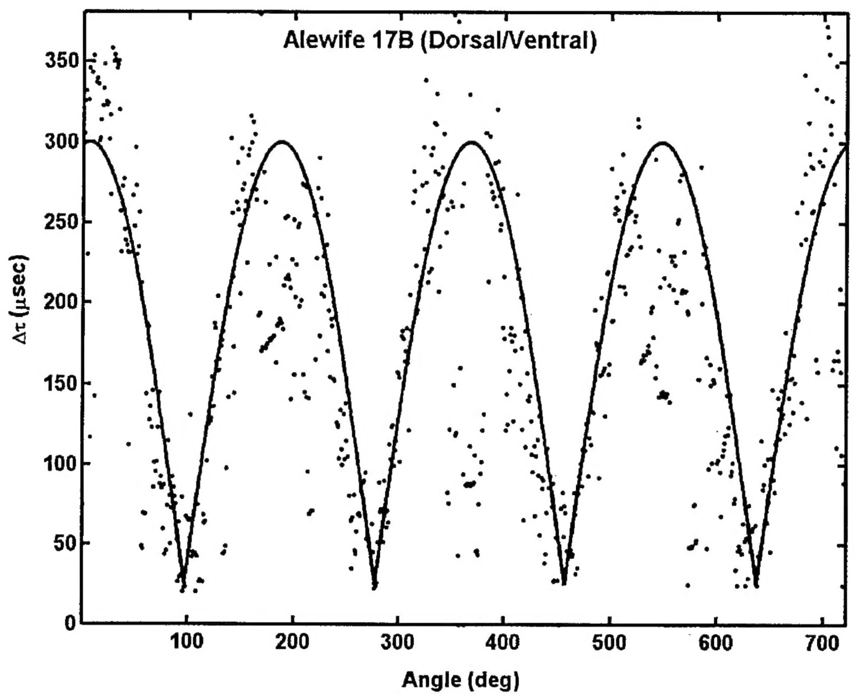

Lateral Plane
1
0
-1
Normal Incidence
5.3
5.5
5.7
Normalized Compressed Pulse Output
1
0
-1
Near Normal
5.3
5.5
5.7
1
0
-1
Oblique
5.3
5.5
5.7
Time Delay (msec)

Figure 3



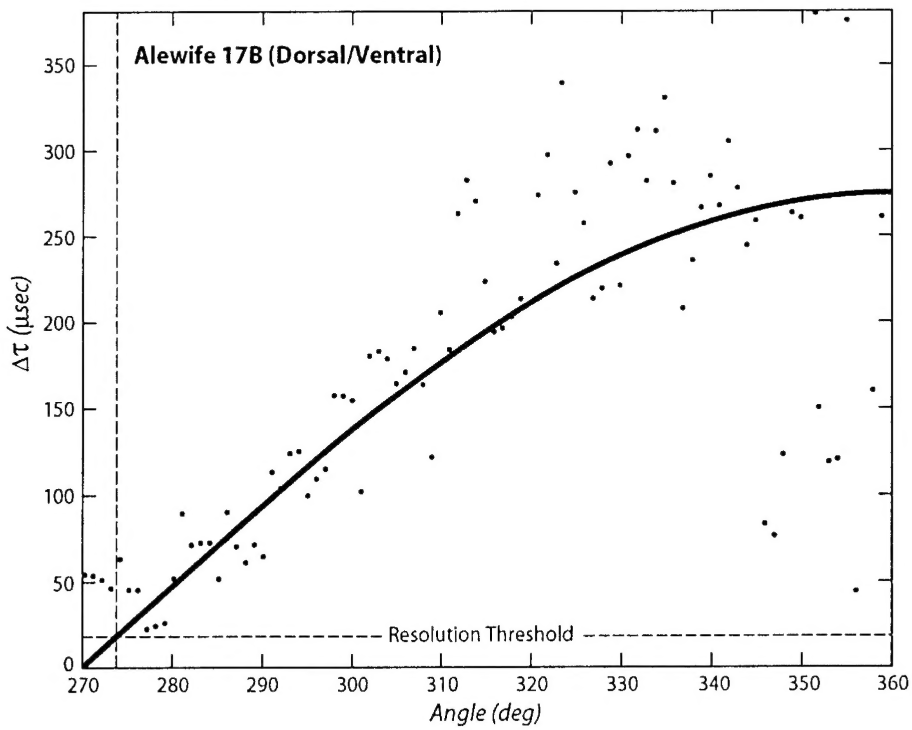
Normalized Compressed Pulse Output
Head-on
180
140
100
60
20
Tail-on
Orientation (deg)
Δτ
0
100
200
300
400
Time Delay (μsec)

Figure 4



Alewife 17B (Dorsal/Ventral)
350
300
250
200
150
100
50
0
Δτ (μsec)
100
200
300
400
500
600
700
Angle (deg)

Figure 5



Alewife 17B (Dorsal/Ventral)
350
300
250
200
150
100
50
0
Δτ (μsec)
Resolution Threshold
270
280
290
300
310
320
330
340
350
360
Angle (deg)

Figure 6

Subject: **Fish school acoustics / whale scattering**
Date: Wed, 28 Aug 2002 15:08:26 -0500
From: max.deffenbaugh@exxonmobil.com
To: tstanton@whoi.edu

Tim,

I enjoyed talking with you last week. I'm particularly interested in the acoustical properties of schools of fish. I think I see some analogies between that problem and predicting the attenuation of elastic waves propagating through rocks (which is a problem we care about.) Perhaps we could talk some more about that when you get back from your trip.

On another topic... When we conduct seismic surveys in areas where marine mammals may be present, there is commonly the restriction that the survey must pause whenever whales are within say 1km of the seismic vessel. The problem is knowing when the whales are there. Trained observers with binoculars are often placed on seismic vessels to look for whales, but there is no guarantee that the animals will breach when the observer is looking. There have been a few attempts at localizing and identifying the whales passively using their vocalizations. Unfortunately, many species do not vocalize frequently. Very recently, there has been some discussion of using active sonars to look for whales, but the sonar wouldn't tell us whether a target is a whale or something else.

If you thought of the whale as a GIANT zooplankton, do you think you might have any interest in working on whale species identification from acoustic backscattering?

In addition to the usual funding sources for marine mammals work, there will soon be a new source. The International Association of Geophysical Contractors (IAGC) is coordinating raising money from the oil industry to specifically support studies related to understanding and mitigating the impact of seismic surveys on marine mammals. They hope to have $2M per year available toward this end. Grant proposals will be reviewed by a committee of academics. Mark Johnson has had some interaction with them regarding his whale tags.

Max